PROPULSION MODELING TECHNIQUES AND APPLICATIONS FOR THE NASA DRYDEN X-30 REAL-TIME SIMULATOR

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Abstract

The current National Aero-Space Plane (NASP) Program Phase 2 design and development process includes developing flight-envelope expansion techniques, with the definition of range requirements, flight maneuver techniques, and abort scenarios. This is being accomplished with the NASA Dryden NASP Engineering Simulator (NES) by the Edwards AFB government flight test team. The team is made up of NASA Dryden Flight Research Facility and Air Force Flight Test Center personnel. Because the current contractor simulation models focus on the single-stage-to-orbit (SSTO) mission, the Edwards team has developed unique real-time propulsion modeling techniques to perform the necessary simulation flight studies. Flexible, multifaceted propulsion models were developed to allow for flight operational assessment of design features or to perform design trade studies. These models account for expanded operating conditions and internal propulsion performance characteristics, and include advanced engine throttling concepts. By using these techniques, excellent results were obtained in producing high-fidelity, advanced ramjet–scramjet propulsion models that were structurally simple and computationally fast for real-time application. Such modeling concepts should be considered for general use in airbreathing hypersonic flight research vehicle simulations when developing new flight test techniques for this class of aircraft.

Nomenclature

A_c	reference inlet cowl area
A_∞	free-stream capture area
C_M	pitching moment coefficient
C_T	coefficient of thrust
CONUS	continental United States
F	propulsive force
HUD	head-up display
I_{sp}	specific impulse
JPO	Joint Program Office
L	reference length
LOX	liquid oxygen
M	Mach number or pitching moment
NASP	National Aero-Space Plane
NES	NASP Engineering Simulator
NPO	National Program Office
P	static pressure
PLA	power lever angle
$\bar{q}$	dynamic pressure
SSTO	single-stage-to-orbit (condition)
T	static temperature
α	angle of attack
Δ	difference between two values
ϕ	fuel-to-air equivalence ratio

Subscripts

∞	free-stream value
0	propulsion system station 0
$1'$	table value 1
2	propulsion system station 2
$2'$	table value 2
3	propulsion system station 3
$3'$	table value 3
A	axial thrust component
c	inlet cowl station
M	pitching moment
N	normal thrust component
ref	SSTO reference flight conditions
s	ramjet combustor normal shock location
T	thrust component or contribution

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Introduction

The National Aero-Space Plane (NASP), designated the X-30, is being developed to advance and validatc the requisite technologies needed for airbreathing hypersonic flight within the Earth's atmosphere up to and including single-stage-to-orbit (SSTO). This includes development of major technologies such as materials and structures, controls, low-speed propulsion concepts, ramjet–scramjet airbreathing engines, cryogenic propellants, vehicle thermal management, and other aircraft subsystems. The ultimate goal is a flight vehicle to provide the final integration and validation of these technologies.

Figure 1 is an artist's concept of the X-30 aircraft. The flight vehicle is designed to be a hydrogen-powered airbreathing propulsion system aircraft capable of horizontal takeoff from a conventional runway to orbit. It will operate at high dynamic pressures to maximize airbreathing engine performance. This will result in very high airframe temperatures and heat flux rates requiring active cooling and passive thermal protection. The propulsion system includes a low-speed engine system to approximately Mach 3, ramjet operation from Mach 3 to approximately Mach 6, and a scramjet mode from Mach 6 and above. A small rocket system is planned for final orbit insertion and circularization.

The NASP research flight vehicle program consists of three distinct phases. Phase 1 was a concept evaluation period. The program is currently in the latter stages of the Phase 2 period, which includes the development and validation of the requisite technologies needed to build an actual flight vehicle. If approved in April 1993, Phase 3 will include detailed vehicle design and fabrication as well as flight test and research activities. The first flight is currently slated for late 1997 with the goal of achieving SSTO by 1999 after a two-year envelope expansion phase.

The X-30 vehicle will experience a unique flight-envelope expansion program. The program will feature a very large hypersonic flight envelope over a Mach number range to Mach 25, severe dynamic pressure loads, and an extreme aerodynamic heating environment. The challenge of this operating envelope is coupled with a unique, never-before-flown airbreathing propulsion system, complex integrated control systems for guidance and trajectory control, active cooling, and advanced structures. The entire continental United States (CONUS) will be needed to expand and explore the X-30 flight envelope. This will require complex flight test plans and range requirements for single-site operation from Edwards AFB. Flight test planning is required early in the program to develop requisite envelope expansion concepts, identify operational design features, and define range requirements.

The X-30 flight test planning and flight operational assessment has necessitated extensive development of a NASA Dryden Flight Research Facility (NASA Dryden) hypersonic real-time simulator. This is especially true in the propulsion modeling area. The large hypersonic flight envelope, multiengine modes, unique ramjet–scramjet propulsion performance, and operational requirements for flight-envelope expansion were the impetus for developing new modeling techniques and models. The Edwards government NASP flight test team consists of personnel from NASA Dryden and the Air Force Flight Test Center. Since 1986 the team has worked to expand and develop X-30 simulation technology, particularly in the modeling area. A highly flexible real-time simulation was developed with both generic unclassified hypersonic vehicle models and specific NASP configuration simulations. These have proved invaluable to the team for flight planning, design trade studies, and overall simulation technology development. Simulation work has included SSTO trajectory studies, vehicle performance and aerothermodynamics, hypersonic guidance and control techniques, and flying qualities.

This paper will present an overview of the flight planning activities to date, including a discussion of the government flight-envelope expansion concept and other design flight operational assessments. The NASA Dryden NASP real-time simulator configuration will be discussed and hypersonic flight planning simulation propulsion modeling requirements will be described. Finally, an outline of the major propulsion modeling techniques developed by the Edwards flight test team will be given with a discussion of the application value of techniques for developmental hypersonic vehicles.

X-30 Flight-Envelope Expansion Concepts

Because of the large, mostly unknown flight envelope facing the X-30 vehicle on its way to orbital flight, the basic philosophy has been to develop very conservative flight-envelope expansion concepts. This philosophy, coupled with a desire to minimize costly duplication of ground facilities, has resulted in a single test launch and recovery site concept at Edwards AFB in the Mojave Desert of California. The basic idea is to takeoff, climb subsonically, and then accelerate easterly to a conservative cruise speed outbound from Edwards. Then the vehicle will be turned around at a sufficient range, pointing in the direction of Edwards, and accelerated to the new aim envelope expansion Mach number. The aircraft will be stabilized at this test condition to obtain flight clearance data and then the engines will be throttled back or shut down to recover back at Edwards. A ground track example of this concept is outlined in Fig. 2. With the X-30 aircraft headed toward the recovery site upon reaching the new flight-envelope point, a safer recovery can be made if problems arise. This classical stabilized, incremental Mach method has been considered the safest way to carefully approach new flight conditions and–or envelope operating limits. This would include flutter boundaries, thermal limits, engine structural or operating limits, control system critical operating points, and other conditions.

Other flight-envelope expansion concepts are being developed and evaluated. One of the basic flight test requirements is to always have the X-30 vehicle within power-off glide range of a landing site within the CONUS. Of interest then is the maximum Mach number achievable within the CONUS and the downrange and crossrange requirements. This includes assessment of available abort landing sites within the CONUS and assessments such as abort-to-orbit for recovery back to Edwards after one or more Earth orbits.

These and other operational issues are highly dependent on vehicle design, system performance, and operating limits. A key requirement for the stabilized, incremental Mach number envelope expansion method is the need to cruise the vehicle by throttling the engine thrust with either fuel and–or mass flow. This is not straightforward for an accelerator aircraft such as the X-30 airplane. To fully explore potential flight test techniques and carry out the necessary flight planning, the NASA Dryden NASP engineering simulator (NES) had to incorporate the flexible, multifaceted propulsion modeling concept described in this paper.

X-30 Engineering Simulation Description and Evolution

The NASA Dryden real-time, man-in-the-loop simulation development effort began in early 1986 with the introduction of the NASP Revised Government Baseline Vehicle. This vehicle configuration was developed at the NASA Langley Research Center (NASA Langley) from an earlier configuration design by the Dupont Aerospace Corporation of La Jolla, California. This vehicle model was followed by other hypersonic SSTO vehicle configurations including specific NASP contractor configurations.

The NES is a basic fixed-base engineering simulator made up primarily of software containing vehicle performance models. It does not include any aircraft hardware-in-the-loop or any actual vehicle cockpit layouts. These features are still in development. As seen in Fig. 3, the cockpit contains simple shuttle-type vertical tape instruments and analog round-dial instruments, with a standard center control stick and rudder pedals.

System hardware includes a pair of Gould (Encore Computer Corp., Fort Lauderdale, Florida) computers (a 32/9780 and a 32/6750) joined with shared memory. The simulator is also supported by four eight-channel strip chart recorders and an interactive user terminal. Figure 4 shows a block diagram of the simulator configuration. The entire operation can be controlled from the cockpit with both computer keyboard and switch inputs into the simulator. Digital input and output data from the models for aircraft performance and response characteristics can be recorded on a magnetic disk in real time. A hard copy of any user terminal page is obtainable. A 25-in. monitor displays two switchable visual scenes, each generated by a Silicon Graphics IRIS 4D/80GT (Silicon Graphics, Inc., Mountain View, California) display. One scene, shown in Fig. 5, is the head-up display (HUD) superimposed over the traditional out-the-window view of Rogers Dry Lake and the surrounding local area. The other scene (Fig. 6), is an overhead view of the vehicle's ground track over five southwestern states. Two 19-in. monitors with engineering displays are driven by a MassComp 5400 (Concurrent Computer Corp., Westford, Massachusettes) workstation. Figure 7 shows one of these monitors, which provides the vehicle CONUS ground tracking and abort cardioid used to designate potential emergency landing sites. Figure 8 shows the other monitor, which is an engineering data information display. This monitor shows propulsion, aerothermodynamic heating, sonic boom overpressure, propellant, and flight Mach number and altitude information in real time along the vehicle flightpath.

Simulation software is highly modular and written in FORTRAN 77 language. Generic and vehicle-specific models include full six-degree-of-freedom oblate rotating Earth and gravity models, an atmospheric model, an aerodynamic heating model, and a sonic boom overpressure model. Other vehicle models include aerodynamics, propulsion, actuator, mass properties, controls, and guidance and navigation.

Edwards Flight Test Team Flight Planning Studies

The Edwards flight test team flight planning simulation studies have centered on envelope expansion concept development and abort scenario development–evaluation for the evolving NASP-specific configurations. This includes an operational, range, and safety assessment of the vehicle. In addition to this fundamental task, the Edwards team has supported the NASP Joint Program Office (JPO) and its government partners, the contractors, and the National Program Office (NPO) in various design trade studies and flight operational assessments of design issues.

Additionally, the team has conducted special studies in such areas as engine and airframe duty cycle definition to assess potential operating limit impacts and assist in defining vehicle life. Other special tasks have included SSTO trajectory studies and performance optimization for SSTO, vehicle heat load comparisons between the SSTO mission profile and the flight-envelope expansion missions, vehicle performance sensitivity studies, and handling qualities evaluation. Takeoff and landing performance has been evaluated from a technique and flying qualities perspective. Unpowered landing approach technique has been studied extensively.

These study results, fed directly into the vehicle design process, have greatly benefited the government flight test team in design evaluations. In addition, lessons learned from this work have been instrumental in assisting the government and contractor national team in the development of key program planning documents. These include the Flight Test Plan and the Systems Requirements Document.

X-30 Propulsion Modeling Requirements

To properly model the X-30 propulsion system for real-time implementation on the NES simulator, several prerequisites needed definition. First, the models had to be compact and computationally efficient to conserve simulation computation time and storage capacity. Implementing and running several engine-cycle computer programs in real time was impractical. The multiengine mode nature of the airbreathing propulsion system had to be incorporated in a single model. Proper consideration was given to correct modeling of engine mode transition between the low-speed, ramjet, and scramjet engines. Additionally, a separate rocket model had to be incorporated to work with the airbreathing system across the Mach number range.

The models' propulsion performance had to be modeled as a function of flight conditions, engine power (fuel flow) settings, and atmospheric effects. This flexibility was needed to carry out various studies and develop flight test techniques for flight conditions other than those of the SSTO. Simulation models required a sufficient expansion of angle-of-attack dependency to allow for cruise and turns. Also required was a large dynamic pressure range within operating limits of the engine combustion process and cooling requirements that would allow reasonable cruise missions. Cruise is desirable at low dynamic pressure at high Mach number to minimize heat loads on the airframe and systems. An ancillary aspect of the cruise capability was the engine fuel and mass flow throttleability required to modulate thrust to cruise conditions over a large Mach number and altitude range.

Only steady-state models have been used to date, although dynamic modeling techniques are available and will be incorporated. Flight condition modeling included wide angle-of-attack, dynamic pressure, and Mach number ranges. Angle-of-sideslip effects have not been modeled yet. In addition, a flowpath liquid oxygen (LOX) augmentation capability has been modeled, but the external burning technique for base drag reduction has not been accounted for.

Separate models were developed for the external thrust and specific impulse performance, the internal engine pressure and temperature performance, and the variable engine geometry mass flow throttling. As seen in Fig. 9, separately controllable throttles were built into the cockpit for the airbreather mass and fuel flow control and the rocket throttling. The mass flow throttle controls the engine variable geometry simultaneously for all flowpaths to regulate mass flow just as the single fuel flow throttle does for the propellant. The single rocket throttle controls all rocket thruster modules. One throttle is unused. Engine fuel throttling can be performed manually by the pilot or scheduled automatically as a function of Mach number and dynamic pressure.

Expanded Propulsion Modeling Techniques

The thrust and specific impulse propulsion model for the airbreather included the three engine modes described previously. Thrust and thrust-induced pitching moment were modeled in coefficient form. They were modeled with dynamic pressure ($\bar{q}$) and a reference inlet cowl area as a function of Mach number (M), angle of attack (α), and the fuel equivalence ratio (ϕ), which is defined as the actual fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio. An important aspect of this technique was that it reduces the dimensionality of the model from four (as a $f(M, \alpha, \phi, \bar{q})$) to three (as a $f(M, \alpha, \phi)$) independent variables. This makes the model implementation more compact and computationally efficient. The specific impulse (I_{sp}) over the flight envelope was modeled with reference to the SSTO specific impulse as a function of the same variables. Figure 10 shows a flowchart of the technique.

Propulsion model expansion was computed from a NASA Langley-developed computer code known as SRGULL.[1] The SRGULL program is a two-dimensional nose-to-tail ramjet–scramjet engine-cycle code. The program is made up of a combination of two-dimensional Euler inviscid flow codes for the inlet and nozzle, and a one-dimensional multistep combustor code. A Spalding-Chi boundary-layer code was embedded to apply viscous corrections to the inviscid calculation. This was done to account for effects of skin friction and heat transfer throughout the flowpath from nose to tail, including the combustor section. An eight-specie chemical kinetics model was included to account for the effects of chemical kinetics on the combustor and nozzle flows. Inputs to SRGULL included flight conditions of Mach number, altitude or dynamic pressure, angle of attack, and power setting along with a definition of the vehicle lower fuselage geometry. This allowed for the rapid calculation of propulsion forces and moments for the model database buildup. Cowl-to-tail axial and normal thrust components as well as the thrust pitching moment contribution were computed.

Data furnished by the NASP NPO engine contractors were used to match the SSTO performance predictions and maintain model commonality over the available database variable range. The thrust, moment, and specific impulse data were converted to coefficient (thrust and moment) or SSTO-reference ratio (I_{sp}) form and implemented in the propulsion model. This database was then extrapolated with SRGULL trend analysis results to larger angle-of-attack values of approximately 15°, and to combustion limit values of equivalence ratio and dynamic pressure. Typically, most contractor-furnished models concentrated on defining the models only to low angles of attack, and high dynamic pressure and fuel-to-air equivalence ratio values corresponding to the SSTO trajectory. Little or no data were available for cruise at low dynamic pressure and fuel-to-air equivalence ratio or at maneuvering angles of attack such as in a turn. The coefficient method advantage was that the model could be expanded easily in dynamic pressure from the high SSTO values common in the contractor models to very low dynamic pressure conditions at high altitude. Figure 11 shows an example of the model results for the axial thrust component and the specific impulse. The figure portrays excellent SRGULL results agreement within nominally ± 5 percent of the contractor propulsion data over the applicable range. It provided realistic trend data for extending the model to desired levels beyond the available database.

The coefficient of thrust and moment, and I_{sp} data were assumed constant with dynamic pressure. However, the data were a slight function of dynamic pressure, which was corrected for as a function of Mach number. The dynamic pressure correction was stored in the model as a function of Mach number and angle of attack and added to the basic model coefficients. Detailed discussions of the techniques described here and following are beyond the scope of this paper.

The LOX augmentation models were also developed for the engine to study thrust enhancement techniques. These models allow for automatic scheduling of the LOX augmentation at various preselected Mach numbers and over a range of oxidant-to-fuel ratios.

Internal Propulsion Modeling Technique

The internal engine flowpath static pressures and temperatures were modeled as a function of flight condition and power setting. This was required to track potential engine pressure and thermal operating limits during the flight planning studies. An extra value was the ability to define the engine duty cycle during the SSTO mission and typical flight test missions. The technique again involved the use of NASA Langley's SRGULL steady-state engine-cycle program to build the pressure and temperature databases as a function of engine station location. No engine flowpath or control dynamics were modeled. Figure 12 shows a summary schematic of the technique and model structure.

The variables were referenced to corresponding SSTO conditions and anchored to free-stream conditions of pressure and temperature. Engine stations modeled included the inlet throat (station 2), ramjet combustor normal shock location (station s), and combustor exit (station 3). Conditions at each engine station had to be determined beginning from free stream to model the pressure and temperature changes from station to station throughout the length of the engine. Temperature and pressure ratios were modeled specifically as a function of Mach number, angle of attack, and fuel equivalence ratio in a range corresponding to that of the external propulsion model. Ratios were assumed constant with dynamic pressure.

The opinion of the Edwards team is that the modeling techniques discussed previously for expanded and internal propulsion modeling will be required for developmental flight test planning for this class of hypersonic airbreathing vehicles. They are generally applicable to a wide range of such vehicles for modeling vehicle performance in either the batch or real-time simulation modes.

Thrust Modulation Modeling Techniques

As discussed earlier, the current government NASP flight-envelope expansion concept is based on the stabilized, incremental Mach number expansion technique. In turn, this technique relies on the ability to throttle or modulate the airbreather engine thrust to a stabilized cruise condition. This is particularly difficult for the NASP SSTO hypersonic class of aircraft that are designed to be high-speed accelerators to orbit with limited cruise design capability. Fuel flow throttling alone won't allow sufficient thrust modulation because of practical engine operating limitations such as a minimum combustor pressure limit for flame holding and combustion. This is particularly critical in the ramjet mode. Additionally, the scramjet typically has minimum engine cooling requirements using the circulated fuel for cooling the entire airframe structure. Once a minimum fuel flow condition is reached the aircraft normally would still have a large thrust residual. The only other way to reduce the thrust level is by throttling-down the inlet mass flow using available variable engine geometry.

This led to the idea for developing an engine mass flow throttling model using the SRGULL program to calculate the modulation of engine mass flow. The thrust coefficient components and pitching moment contribution described in an earlier section were calculated with reduced mass flow and modeled as a function of the same variables described previously. The objective was to model the mass flow throttling so that an efficient, linear variation of thrust could be obtained using a separate cockpit throttle from the one used to modulate fuel flow. A schematic of the control schedule concept is shown in Fig. 13. Development and implementation of this control schedule allowed for vehicle stabilization over virtually its entire flight envelope. This was done without compromising minimum combustor pressure limits or engine minimum cooling fuel flow limits. Also modeled and compensated for are the inlet supersonic flow unstart limits, especially for the ramjet mode. The geometry control scheduling is automatic and programmed as a function of the mass flow throttle lever angle.

Figure 14 shows the axial coefficient of thrust and specific impulse as a function of percent mass flow throttle setting for the ramjet at Mach 4 and for the scramjet at Mach 6. The data shown are for a given dynamic pressure, angle of attack, and fuel-to-air equivalence ratio flight condition. The figure clearly illustrates the technique's effectiveness in producing a large, linear thrust modulation capability. The developed throttling technique's advantage is that it allows easy tailoring of the engine thrust and–or specific impulse response for any desirable control characteristic. This technique has excellent utility for flight studies and other flight applications such as hypersonic cruiser aircraft.

Concluding Remarks

The Edwards AFB government flight test team of the National Aero-Space Plane Program has successfully developed several innovative propulsion modeling techniques for real-time simulation. These techniques were required to allow maximum flexibility in ongoing flight planning and flight study activities to develop flight-envelope expansion techniques and to address flight operational issues. Technique development has included a thrust and specific impulse model expanded beyond the normal SSTO flight conditions to allow for cruise and maneuvering flight. In addition, an internal flowpath propulsion model was developed to better monitor engine operating limits and determine duty cycles. A powerful thrust modulation technique was developed through the control of mass flow and fuel flow. This has allowed a greatly expanded cruise envelope capability, which is needed for some of the flight-envelope expansion concepts being developed.

These modeling techniques have been applied to the NASA Dryden Flight Research Facility National Aero-Space Plane (NASP) Engineering Simulator, yielding high-fidelity simplified, and computationally fast real-time simulation models. These techniques are generally applicable to a wide range of airbreathing hypersonic vehicles for modeling vehicle performance in the batch or real-time simulation modes. It is the opinion of the Edwards team that these modeling techniques will be required for developmental flight test planning and for other flight applications such as hypersonic cruiser aircraft.

References

[1]Pinckney, S. Zane, and Walton, James T., *Program SRGULL: An Advanced Engineering Model for the Prediction of Airframe-Integrated Subsonic/Supersonic Hydrogen Combustion Ramjet Cycle Performance,* NASP TM-1120, 1991.

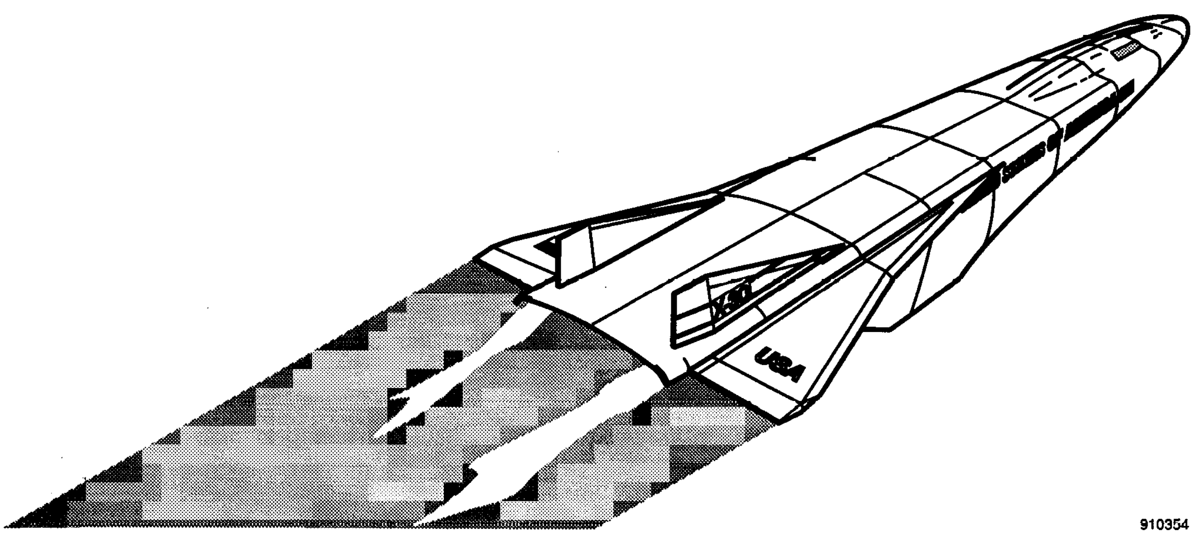

Fig. 1 Artist's concept of the X-30 vehicle.

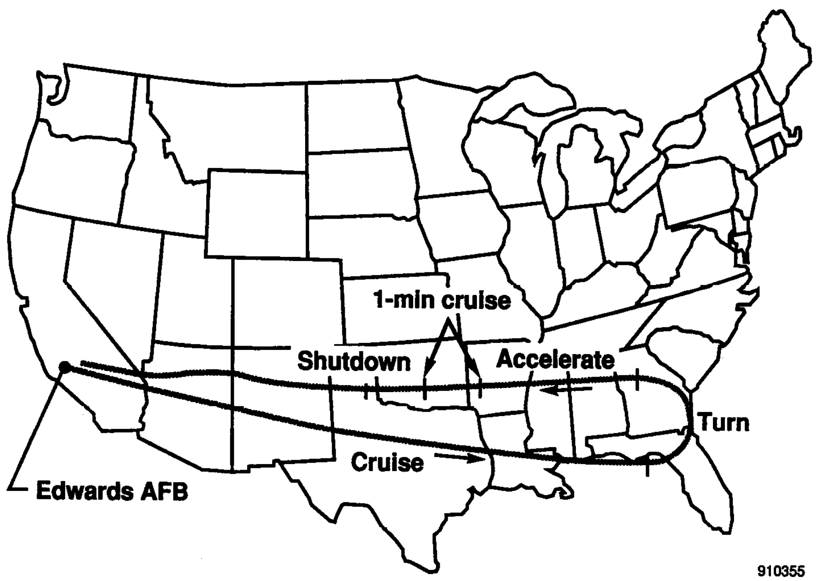

Fig. 2 Typical envelope expansion flight test mission.

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Fig. 3 NES cockpit layout.

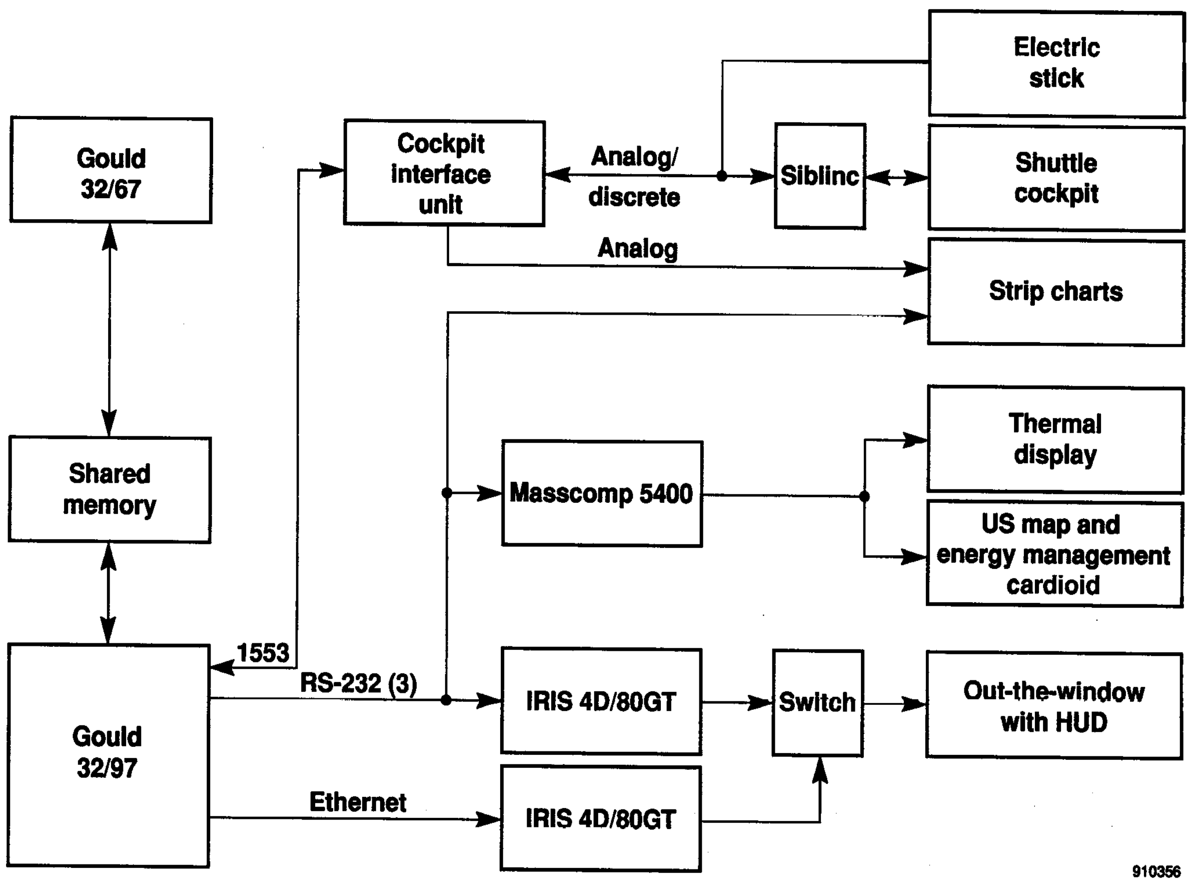

Fig. 4 Current simulation configuration.

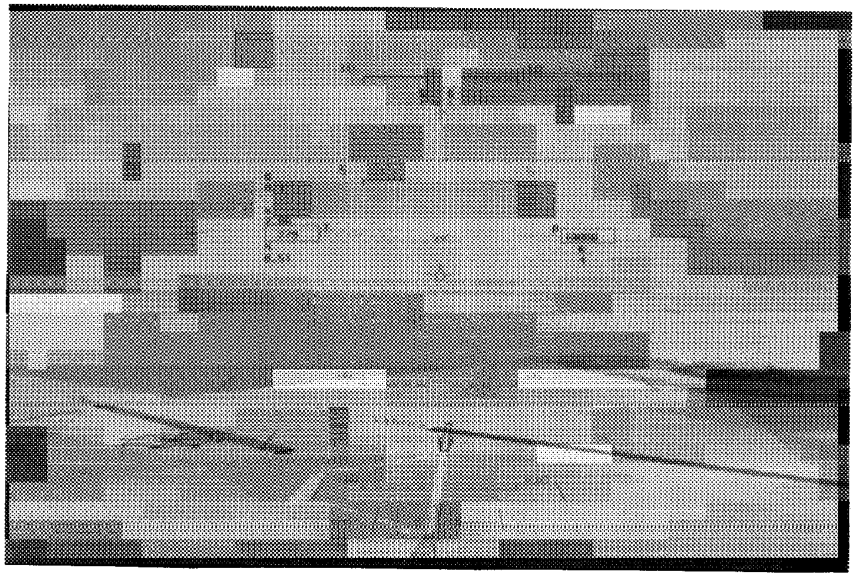

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Fig. 5 NES out-the-window scene.

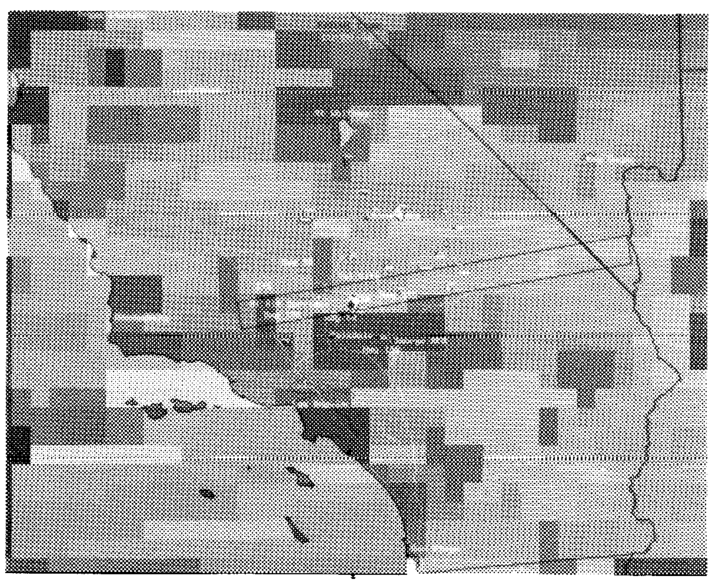

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Fig. 6 Local area display.

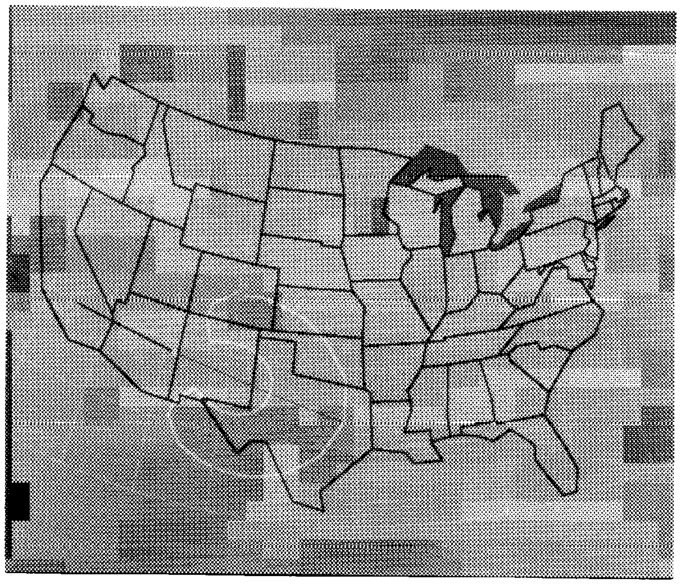

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Fig. 7 CONUS map with recovery cardioid.

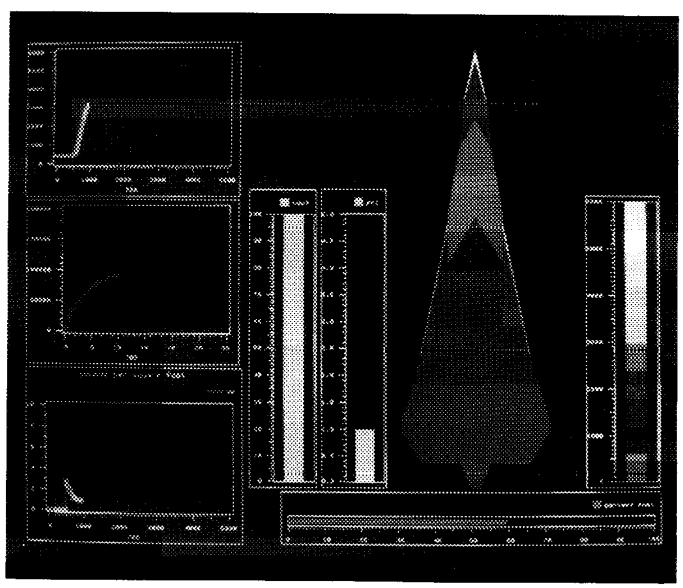

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Fig. 8 Engineering data display.

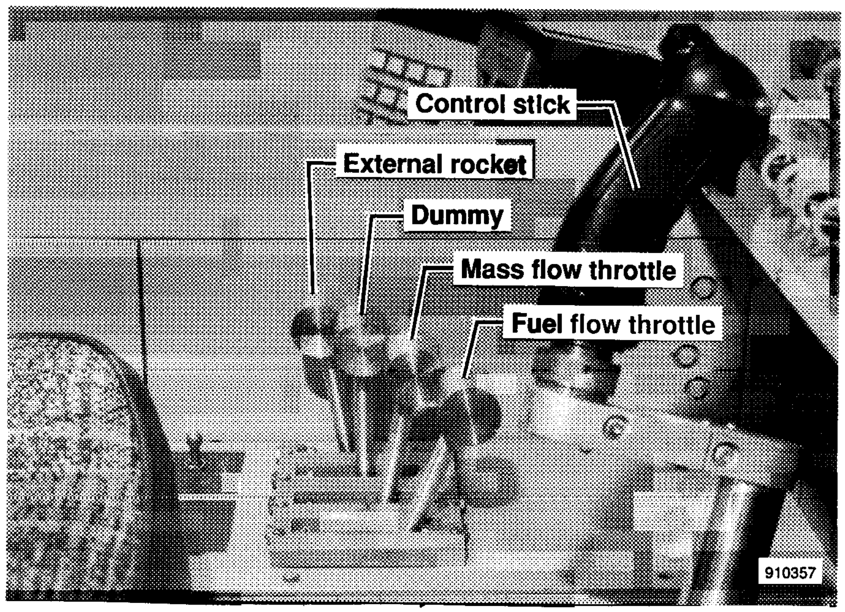

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Fig. 9 NES engine throttles.

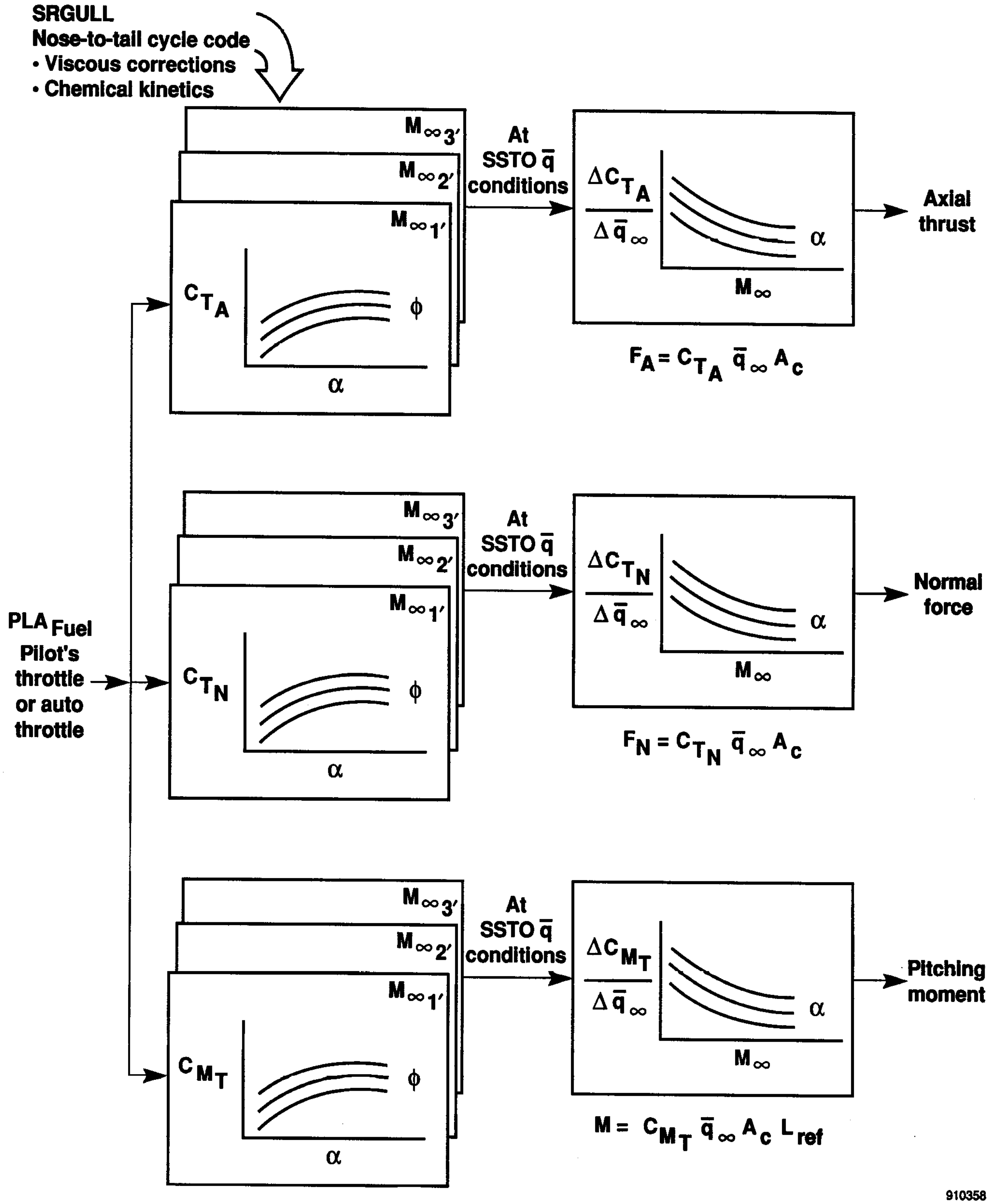

Fig. 10 Scramjet propulsion modeling technique.

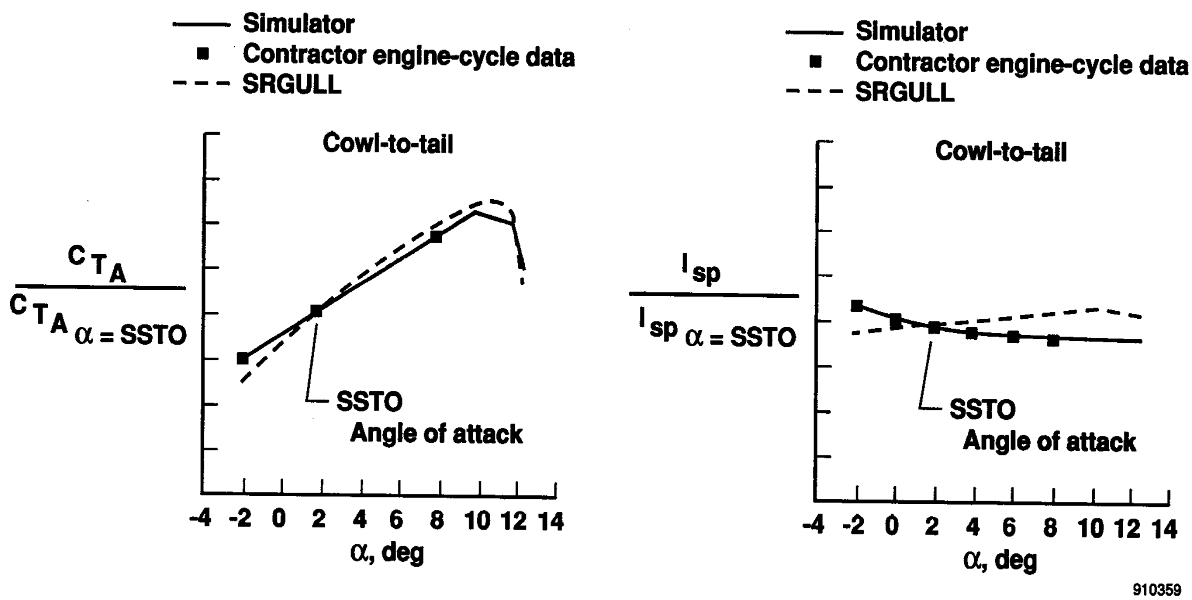

Fig. 11 Typical scramjet propulsion model, results from SRGULL and simulation; $\phi = 1.0$.

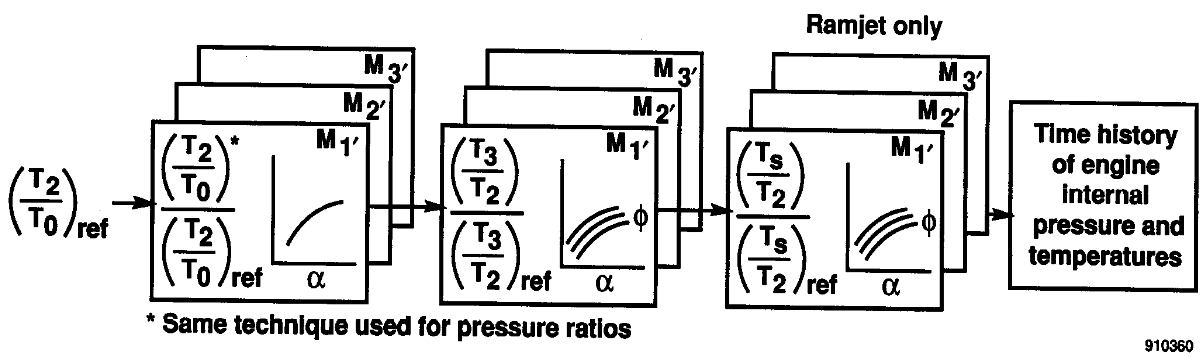

Fig. 12 Internal propulsion modeling technique.

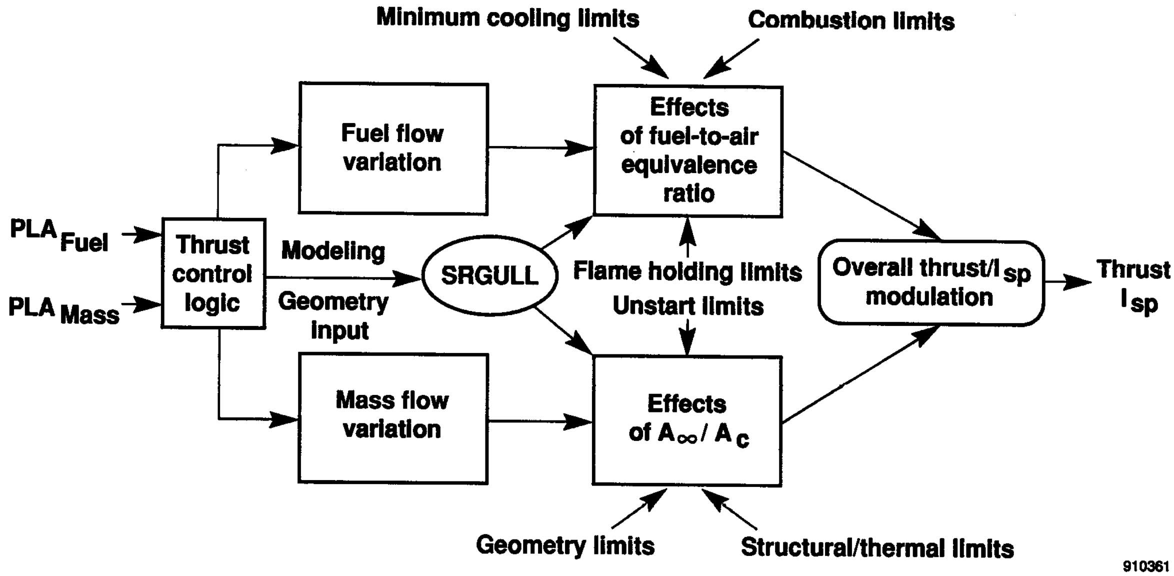

Fig. 13 Propulsion throttling concept using SRGULL model calculations.

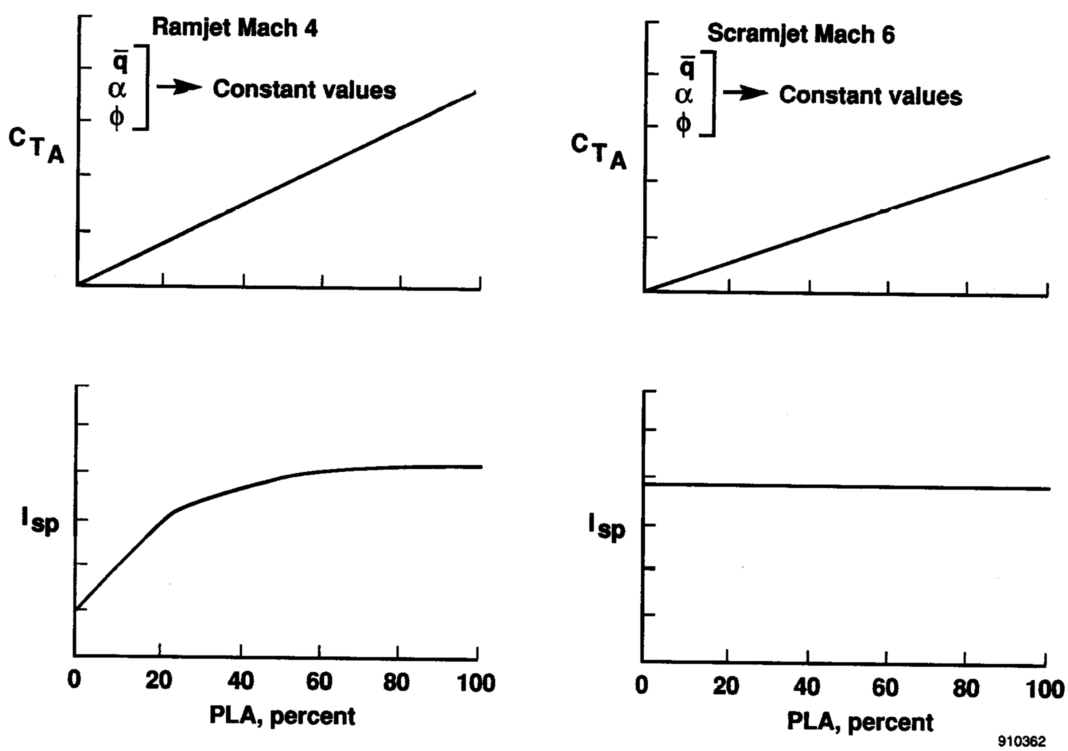

Fig. 14 Mass flow thrust modulation effectiveness.